Recent Advances in Photonic Devices for Optical Computing

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Introduction

Computers have enhanced human life to a great extent. The speed of conventional computers is achieved by miniaturizing electronic components to a very small micron-size scale so that those electrons need to travel only very short distances within a very short time. The goal of improving on computer speed has resulted in the development of the Very Large Scale Integration (VLSI) technology with smaller device dimensions and greater complexity. Last year, the smallest-to-date dimensions of VLSI reached 0.08 μm by researchers at Lucent Technology. Whereas VLSI technology has revolutionized the electronics industry and established the 20th century as the computer age, increasing usage of the Internet demands better accommodation of a 10 to 15 percent per month growth rate. Additionally, our daily lives demand solutions to increasingly sophisticated and complex problems, which requires more speed and better performance of computers.

For these reasons, it is unfortunate that VLSI technology is approaching its fundamental limits in the sub-micron miniaturization process. It is now possible to fit up to 300 million transistors on a single silicon chip. It is also estimated that the number of transistor switches that can be put onto a chip doubles every 18 months. Further miniaturization of lithography introduces several problems such as dielectric breakdown, hot carriers, and short channel effects. All of these factors combine to seriously degrade device reliability. Even if developing technology succeeded in temporarily overcoming these physical problems, we will continue to face them as long as increasing demands for higher integration continues. Therefore, a dramatic solution to the problem is needed, and unless we gear our thoughts toward a totally different pathway, we will not be able to further improve our computer performance for the future.

Optical interconnections and optical integrated circuits will provide a way out of these limitations to computational speed and complexity inherent in conventional electronics. Optical computers will use photons traveling on optical fibers or thin films instead of electrons to perform the appropriate functions. In the optical computer of the future, electronic circuits and wires will be replaced by a few optical fibers and films, making the systems more efficient with no interference, more cost effective, lighter and more compact. Optical components would not need to have insulators as those needed between electronic components because they don't experience cross talk. Indeed, multiple frequencies (or different colors) of light can travel through optical components without interfacing with each others, allowing photonic devices to process multiple streams of data simultaneously.

Why Use Optics for Computing?

Optical interconnections and optical integrated circuits have several advantageous over their electronic counterparts. They are immune to electromagnetic interference, and free from electrical short circuits. They have low-loss transmission and provide large bandwidth; i.e. multiplexing capability, capable of communicating several channels in parallel without interference. They are capable of propagating signals within the same or adjacent fibers with essentially no interference or cross-talk. They are compact, lightweight, and inexpensive to manufacture, and more facile with stored information than magnetic materials.

We are in an era of daily explosions in the development of optics and optical components for computing and other applications. The business of photonics is booming in industry and universities worldwide. It is estimated that photonic device sales worldwide will range between $12 billion and $100 billion in 1999 due to an ever-increasing demand for data traffic. According to KMI corp., data traffic is growing worldwide at a rate of 100% per year, while, the Phillips Group in London estimates that the U.S. data traffic will increase by 300% annually. KMI corp. also estimates that sales of dense-wavelength division multiplexing equipment will increase by more than quadruple its growth in the next five years, i.e. from $2.2 billion worldwide in 1998 to $9.4 billion 2004. In fact, Future Communication Inc., London, announced this year to upgrade their communication system accordingly. The company's goal is to use wavelength division multiplexing at 10 Gb/s/channel to transmit at a total rate of more than 1000 Tb/s.

Most of the components that are currently very much in demand are electro-optical (EO). Such hybrid components are limited by the speed of their electronic parts. All-optical components will have the advantage of speed over EO components. Unfortunately, there is an absence of known efficient nonlinear optical materials that can respond at low power levels. Most all-optical components require a high level of laser power to function as required. A group of researchers from the university of southern California, jointly with a team from the university of California Los Anglos, have developed an organic polymer with a switching frequency of 60 GHz. This is three times faster than the current industry standard, lithium niobate crystal-based devices. The California team has been working to incorporate their material into a working prototype. Development of such a device could revolutionize the information superhighway and speed data processing for optical computing. Another group at Brown University and the IBM

Almaden Research Center (San Jose, CA) have used ultrafast laser pulses to build ultrafast data-storage devices. This group was able to achieve ultrafast switching down to 100ps. Their results are almost ten times faster than currently available "speed limits". Optoelectronic technologies for optical computers and communication hold promise for transmitting data as short as the space between computer chips or as long as the orbital distance between satellites. A European collaborative effort demonstrated a high-speed optical data input and output in free-space between IC chips in computers at a rate of more than 1 Tb/s. Astro Terra, in collaboration with Jet Propulsion Laboratory (Pasadena, CA) has built a 32-channel 1-Ggb/s earth –to –satellite link with a 2000 km range. Many more active devices in development, and some are likely to become crucial components in future optical computer and networks.

The race is on with foreign competitors. NEC (Tokyo, Japan) have developed a method for interconnecting circuit boards optically using Vertical Cavity Surface Emitting Laser arrays (VCSEL). Researchers at Osaka City University (Osaka, Japan) reported on a method for automatic alignment of a set of optical beams in space with a set of optical fibers. As of last year, researchers at NTT (Tokyo, Japan) have designed an optical back plane with free –space optical interconnects using tunable beam deflectors and a mirror. The project had achieved 1000 interconnections per printed-circuit board, with throughput ranging from 1 to 10 Tb/s.

Optics has a higher bandwidth capacity over electronics, which enables more information to be carried and data to be processed arises because electronic communication along wires requires charging of a capacitor that depends on length. In contrast, optical signals in optical fibers, optical integrated circuits, and free space do not have to charge a capacitor and are therefore faster.

Another advantage of optical methods over electronic ones for computing is that optical data processing can be done much easier and less expensive in parallel than can be done in electronics. Parallelism is the capability of the system to execute more than one operation simultaneously. Electronic computer architecture is, in general, sequential, where the instructions are implemented in sequence. This implies that parallelism with electronics is difficult to construct. Parallelism first appeared in Cray super computers in the early 1980's. Two processors were used in conjunction with the computer memory to achieve parallelism and to enhance the speed to more than 10 Gb/ s. It was later realized that more processors were not necessary to increase computational speed, but could be in fact detrimental. This is because as more processors are used, there is more time lost in communication. On the other hand, using a simple optical design, an array of pixels can be transferred simultaneously in parallel from one point to another. To appreciate the difference between both optical parallelism and electronic one can think of an imaging system of as many as 1000x1000 independent points per mm^2 in the object plane which are connected optically by a lens to a corresponding 1000x 1000 points per mm^2 in the image plane. For this to be accomplished electrically, a million nonintersecting and properly isolated conduction channels per mm^2 would be required.

Parallelism, therefore, when associated with fast switching speeds, would result in staggering computational speeds. Assume, for example, there are only 100 million gates on a chip, much less than what was mentioned earlier (optical integration is still in its infancy compared to electronics). Further, conservatively assume that each gate operates with a switching time of only 1 nanosecond (organic optical switches can switch at sub-picosecond rates compared to maximum picosecond switching times for electronic switching). Such a system could perform more than 10^{17} bit operations per second. Compare this to the gigabits (10^9) or terabits (10^{12}) per second rates which electronics are either currently limited to, or hoping to achieve. In other words, a computation that might require one hundred thousand hours (more than 11 years) of a conventional computer could require less than one hour by an optical one.

Another advantage of light results because photons are uncharged and do not interact with one another as readily as electrons. Consequently, light beams may pass through one another in full-duplex operation, for example without distorting the information carried. In the case of electronics, loops usually generate noise voltage spikes whenever the electromagnetic fields through the loop changes. Further, high frequency or fast switching pulses will cause interference in neighboring wires. Signals in adjacent fibers or in optical integrated channels do not affect one another nor do they pick up noise due to loops. Finally, optical materials possess superior storage density and accessibility over magnetic materials.

Obviously, the field of optical computing is progressing rapidly and shows many dramatic opportunities for overcoming the limitations described earlier for current electronic computers. The process is already underway whereby optical devices have been incorporated into many computing systems. Laser diodes as sources of coherent light have dropped rapidly in price due to mass production. Also, optical CD-ROM discs have been very common in home and office computers.

The Role of NLO in Optical Computing and the Need for New Materials

The field of optical computing is considered to be the most multidisciplinary field and requires for its success collaborative efforts of many disciplines, ranging from device and optical engineers to computer architects, chemists, material scientists, and optical physicists. On the materials side, the role of nonlinear materials in optical computing has become extremely significant. Nonlinear materials are those, which interact with light and modulate its properties.

For example, such materials can change the color of light from being unseen in the infrared region of the color spectrum to a green color where it is easily seen in the visible region of the spectrum. Several of the optical computer components require efficient nonlinear materials for their operation. What in fact restrains the wide-spread use of all optical devices is the inefficiency of currently available nonlinear optical materials, which require large amounts of energy for responding or switching. In spite of new developments in materials, presented in the literature daily, a great deal of research by chemists and material scientists is still required to enable better and more efficient optical materials. Although organic materials have many features that make them desirable for use in optical devices, such as high nonlinearities, Flexibility of molecular design, and damage resistance to optical radiation, their use in devices has been hindered by processing difficulties for crystals and thin films. Our focus is on a couple of these materials, which have undergone some investigation in the NASA/MSFC laboratories, and were also processed in space either by the MSFC group, or others. These materials belong to the classes of phthalocyanines and polydiacetylenes. These classes of organic compounds are promising for optical thin films and waveguides. Phthalocyanines are large ring-structured porophyrins for which large and ultrafast nonlinearities have been observed. These compounds exhibit strong electronic transitions in the visible region and have high chemical and thermal stability up to 400°C. We measured the third order susceptibility of phthalocyanine, which is a measure of its nonlinear efficiency to be more than a million times larger than that of the standard material, carbon disulfide. This class of materials has good potential for commercial device applications, and has been used as a photosensitive organic material, and for photovoltiac, photoconductive, and photoelectrochemical applications.

Polydiacetylenes are zigzag polymers having conjugated (alternating) mobile π-electrons for which the largest reported nonresonant (purely electronic) susceptibility for switching have been reported. Subsequently, polydiacetylenes are among the most widely investigated class of polymers for nonlinear optical applications. Their subpicosecond time response to laser signals makes them candidates for high-speed optoelectronics and information processing.

We have chosen to study these classes of compounds because growth of these films on ordered organic and inorganic substrates under various processing conditions promise to be useful for preparing highly oriented films. One such processing condition of interest to NASA is the effect of microgravity on the structures and properties of thin films and crystals.

The potential benefits of processing optical materials in space were demonstrated by the deposition of copper phthalocyanine in microgravity by physical vapor transport by 3M company (figure 1). Analyses of these films revealed that microgravity grown films are more highly uniaxially oriented than earth-grown films. From figure 1, it is clear that the molecules are stacked toward one direction (uniaxially oriented) for microgravity processed films, and are randomly oriented for ground processed films. Our group observed intrinsic optical bistability and demonstrated an all-optical AND-logic gate (as will be explained later) in vapor-deposited thin films of metal-free phthalocyanine. Optical bistable devices and logic gates are the equivalent of electronic transistors. They switch light ON and OFF. They are also useful as optical cells for information storage. This nonlinear effect could improve dramatically in highly oriented microgravity processed films.

A novel photodeposition process for film photodeposition onto quartz or glass surfaces, developed by members of our group, enabled deposition of polydiacetylene (PDAMNA) films derived from 2-methyl-4-nitroaniline, a well-known organic NLO material, by irradiation of monomer (the building block of a polymer) solutions with UV light. Polydiacetylenes are highly conjugated polymers, i.e., the electrons in the polymer backbone are delocalized and can move freely along the backbone capable of exhibiting very large optical nonlinearities with fast response times (less than 120fs: 1fs = 10^{-15} s). These response times are faster than they are for the fastest electronic switching by more than a hundred times. High quality films that have potential application in integrated optical circuits were produced. Films of PDAMNA that were processed in space on space shuttle flight STS-69 had superior optical quality (i.e. greater homogeneity, fewer defects). This experiment also demonstrates that processing in microgravity offers an opportunity to study certain parameters affecting the production of higher quality materials.

Recent Advances in Photonic Switches at NASA/MSFC

Logic gates are the building blocks of any digital system. An optical logic gate is a switch that controls one light beam by another; it is "ON" when the device transmits light and it is "OFF" when it blocks the light. Recently we demonstrated in our laboratory at NASA/Marshall Space Flight Center two fast all-optical switches using phthalocyanine thin films and polydiacetylene fiber. The phthalocyanine switch is in the nanosecond regime and functions as an all-optical AND logic gate, while the polydiacetylene one is in the picosecond regime and exhibits a partial all-optical NAND logic gate.

To demonstrate the AND gate in the phthalocyanine film, we waveguided two focused collinear beams through a thin film of metal-free phthalocyanine film. The film thickness was ~ 1 μm and a few millimeters in length. We used the second harmonic at 532 nm from a pulsed Nd:YAG laser with pulse duration of 8 ns a long with a cw He-Ne beam at 632.8 nm. The two collinear beams were then focused by a microscopic objective and sent through the phthalocyanine film.

At the output a narrow band filter was set to block the 532 nm beam and allow only the He-Ne beam. The transmitted beam was then focused on a fast photo-detector and to a 500 MHz oscilloscope. It was found that the transmitted He-Ne cw beam was pulsating with a nanosecond duration and in synchronous with the input Nd:YAG nanosecond pulse. The setup described above demonstrated the characteristic table of an AND logic gate. A schematic of the setup is shown in figure 3.

The setup for the picosecond switch was very much similar to the setup in figure 3 except that the phthalocyanine film was replaced by a hollow fiber filled with a polydiacetylene. The polydiacetylene fiber was prepared by injecting a diacetylene monomer into the hollow fiber and polymerizing it by UV lamps. The UV irradiation induces a thin film of the polymer on the interior of the hollow fiber with a refractive index of 1.7 and the hollow fiber is of refractive index 1.2. In the experiment, the 532 nm from a mode locked picosecond laser was sent collinearly with a cw He-Ne laser and both were focused onto one end of the fiber. At the other end of the fiber a lens was focusing the output onto the narrow slit of a monochrometer with its grating set at 632.8 nm. A fast detector was attached to the monochrometer and sending the signal to a 20 GHz digital oscilloscope. It was found that with the He-Ne beam OFF, the Nd:YAG pulse is inducing a week fluorescent picosecond signal (40 ps) at 632.8 nm that is shown as a picosecond pulse on the oscilloscope. This signal disappears each time the He-Ne beam is turned on. These results exhibit a picosecond respond in the system and demonstrated three of the four characteristics of a NAND logic gate as shown in figure (4).

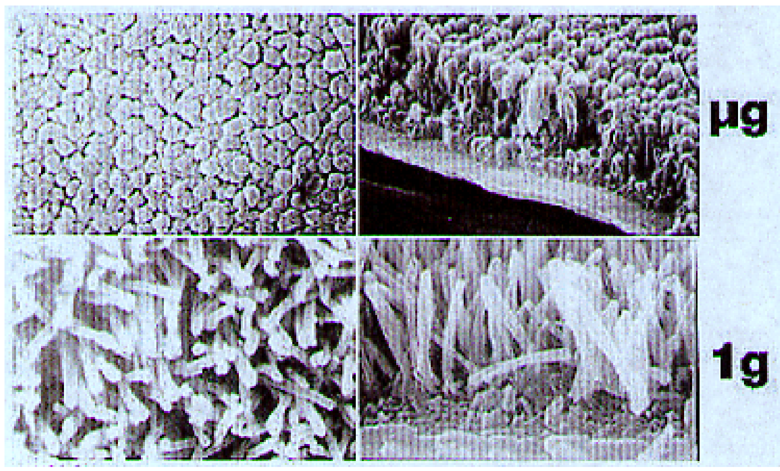
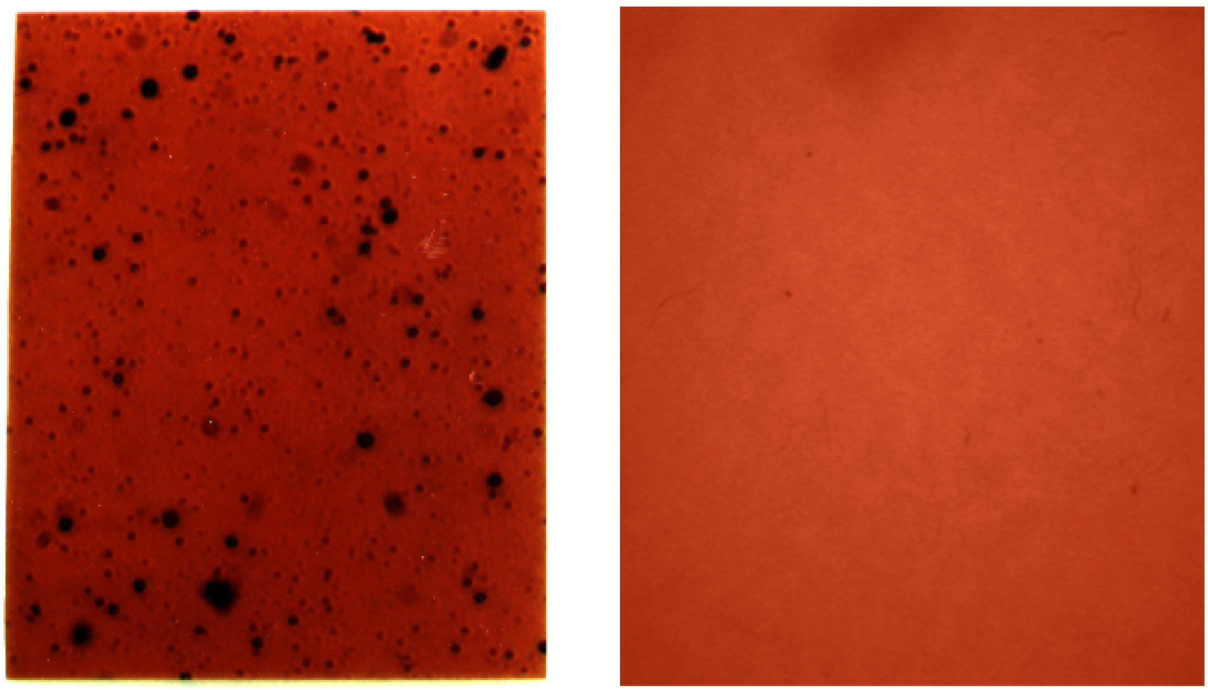


Figure (1). A comparison of a scanning electron micrographs of 1 μm thick films of copper phthalocyanine deposited by physical vapor transport in the 3M PVTOS flight (STS-20) and ground control experiments. In microgravity the film's microstructure is very dense compared to that produced in unit gravity in the presence of convection. This difference in microstructure has a significant affect on the macroscopic film optical properties.



PDAMNA Film (1g) **PDAMNA Film (μg)**

Figure (2). A comparison of a ground-grown polydiacetylene film with a microgravity-grown one. The aggregates are impeded into the film by the fluid convection on the ground, while the microgravity film is almost free of these aggregates where convection is almost absent.

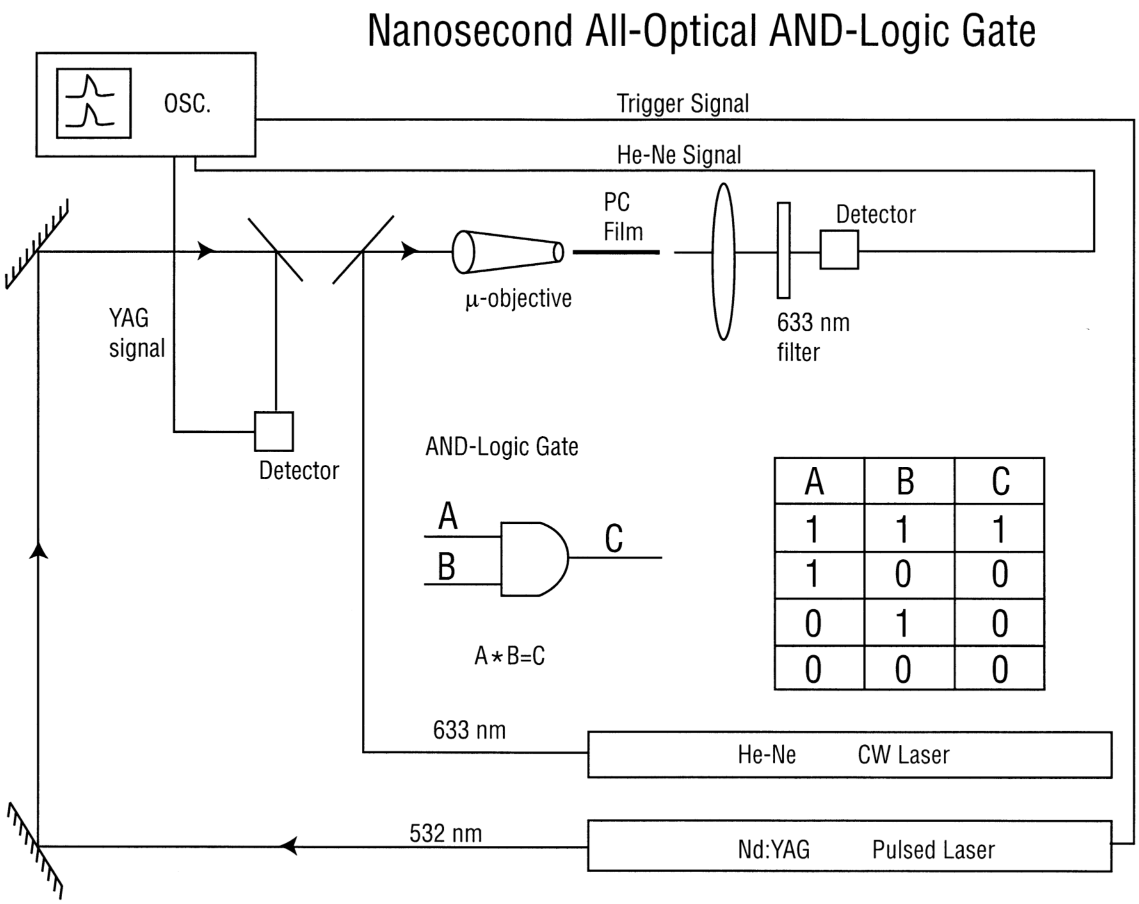
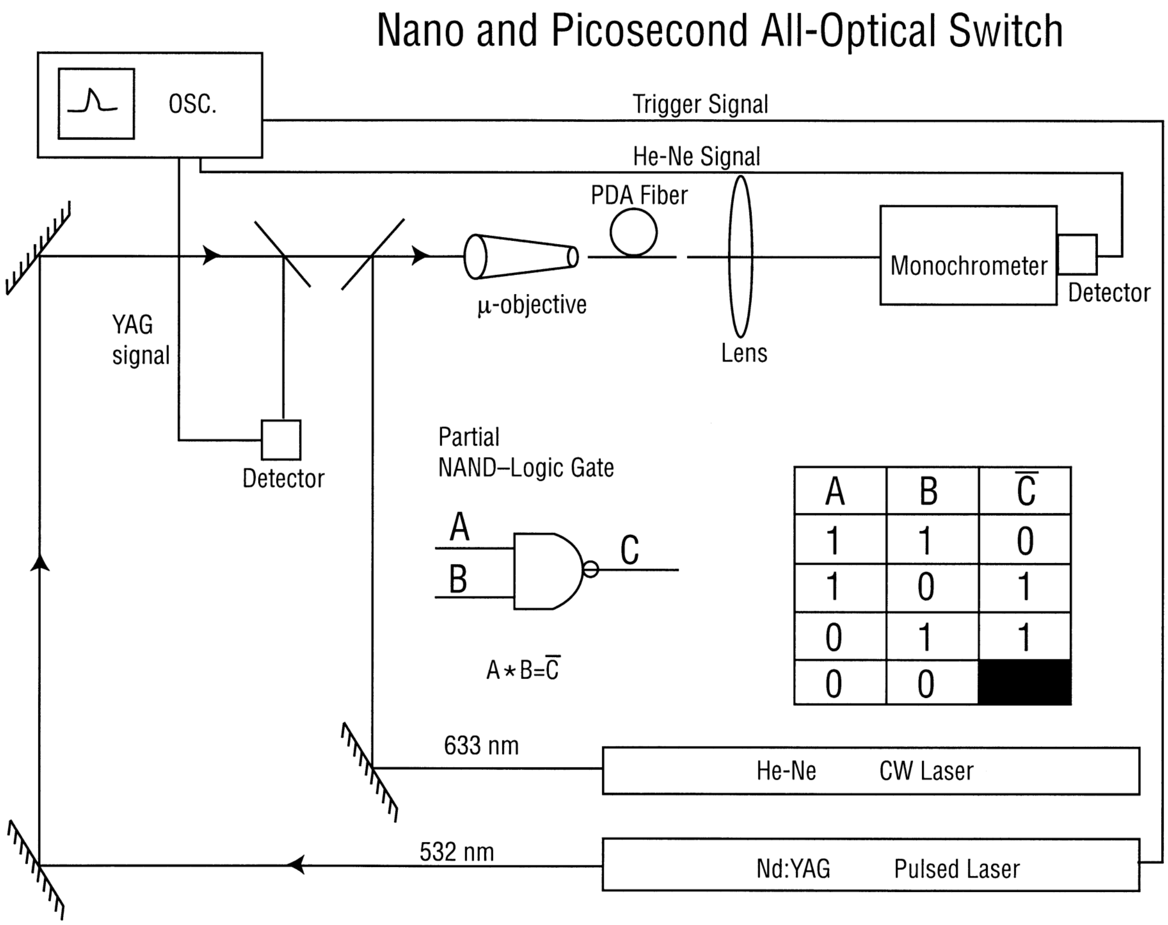


Figure (3). A schematic of the nanosecond all-optical AND logic gate setup.



A	B	$\overline{C}$
1	1	0
1	0	1
0	1	1
0	0	

Figure (4). A schematic of the all-optical NAND logic gate setup.